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DATA-REDUCTION AND ANALYSIS PROCEDURES USED IN NIST's THERMOMECHANICAL PROCESSING RESEARCH

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This report described the data-reduction procedures and computer programs used to reduce and analyze the data obtained with a hot-deformation apparatus. The measured raw data with the apparatus include temperature vs. time, specimen's relative length (dilation) vs. time, actuator movement (stroke) vs. time, and load vs. time. Four computer programs were written for data reduction and analysis to determine the cooling rates, the true stress-true strain curves, the true strain rates, and the phase-transformation temperatures. Local averaging techniques were used to smooth the data of temperature, dilation, stroke, and load. Source codes for the computer programs are included. Example results of the analyses are presented and an example of the program execution is given.

Key words: cooling rate; data averaging; data reduction and analysis; hot deformation; phase-transformation temperatures; thermomechanical processing; strain rate; true stress-true strain curves.

I. INTRODUCTION

This report describes the data-reduction procedures and computer programs used to reduce and analyze the data obtained with a hot-deformation apparatus [1]. The measured raw data include temperature, T, vs. time, t (during cooling); specimen's relative length, l, vs. t (during cooling); machine's actuator (stroke) movement, D, vs. t (during compression); and load, P, vs. t (during compression). These data were initially recorded on a digital storage oscilloscope and then saved onto a floppy disk with a recorder equipped with the oscilloscope.

The data are reduced and analyzed to determine the cooling rates, dT/dt, the true stress-true strain, σ-ϵ, curves, the true strain rates, $\dot{\epsilon}$, and the phase-transformation temperatures in an experiment using a personal computer (PC). Four separate programs, CoolRate.Y, D$l$dtAnal.Y, StrStrn.Y, and StrnRate.Y, were written to perform the analyses of dT/dt, l vs. T, dl/dT vs. T, σ vs. ϵ, and $\dot{\epsilon}$. Phase-transformation temperatures are determined from the analyses of dT/dt and dl/dT vs. T.

The data saved on the oscilloscope's disks cannot be retrieved directly by a PC because of differences in disk formats. Digital-processing software [2] must be used to enable the PC to read the data from the disks. Source codes for the computer programs are included in the Appendixes. Example results of the analyses are presented and an example of the program execution is given.

II. DATA REDUCTION AND ANALYSIS

Computer programs were written in an interactive mode with a commercially available software package [3], which uses reverse Polish notation. This software package was also used in the programs for apparatus control and data acquisition [1]. All programs for data reduction and analysis accept input files in the ASCII format. Because the raw data saved with the oscilloscope's recorder cannot be retrieved directly by a PC due to differences

in disk formats, suitable input data files have to be created from the raw data with digital-processing software [2]. The outputs of the analysis programs, such as dT/dt vs. T, l vs. T, dl/dT vs. T, $\dot{\epsilon}$ vs. total ϵ, and σ vs. ϵ are plotted on the monitor and saved on a hard disk as ASCII files, which can be retrieved and replotted using different graphics packages, if desired.

High levels of random noise are commonly found in the raw data. Thus, it is difficult to draw conclusive trends from the raw data without data averaging. One of the common ways for performing data averaging is to fit all of the data with a single polynomial. This practice is sometimes not adequate because a single polynomial may not fit the whole range of a data set, and a polynomial may also smooth out some details in a data set, such as abrupt changes in slopes. Alternatively, an incremental polynomial method can be used to fit a least-squares polynomial locally. This is the technique we have used here.

The data-averaging technique involves fitting a second-order polynomial to sets of (2N + 1) successive data points, where N is a natural number. The technique works best in data sets with equally spaced points. Because all of the raw data are acquired in equal time intervals, the incremental polynomial method is well suited to our needs. All four programs, CoolRate.Y, DldTAnal.Y, StrStrn.Y, and StrnRate.Y, contain data-averaging routines to smooth data of T, dl, D, and P. The routines include N varying from 0 (no smoothing) to 9 (maximum smoothing) to perform different degrees of smoothing. The formula and coefficients used for the smoothing routines are listed as follows [4].

$$\begin{aligned} Y_{smoothed} = (&C_{-N}Y_{-N} + C_{-N+1}Y_{-N+1} + \ldots + C_{-1}Y_{-1} + C_0Y_0 \\ &+ C_1Y_1 + \ldots + C_{N-1}Y_{N-1} + C_NY_N), \end{aligned}$$

where C_i are the coefficients listed below,
Y_i are the actual data points, and
2N + 1 is the number of points used for the smoothing.

N	C_0	$C_{1,-1}$	$C_{2,-2}$	$C_{3,-3}$	$C_{4,-4}$	$C_{5,-5}$	$C_{6,-6}$	$C_{7,-7}$	$C_{8,-8}$	$C_{9,-9}$	$C_{10,-10}$
1	1	0									
2	$\frac{12}{35}$	$\frac{12}{35}$	$\frac{-2}{21}$								
4	$\frac{7}{21}$	$\frac{6}{21}$	$\frac{3}{21}$	$\frac{-2}{21}$							
4	$\frac{59}{231}$	$\frac{54}{231}$	$\frac{39}{231}$	$\frac{14}{231}$	$\frac{-21}{231}$						
5	$\frac{89}{429}$	$\frac{84}{429}$	$\frac{89}{429}$	$\frac{44}{429}$	$\frac{89}{429}$	$\frac{-36}{429}$					
6	$\frac{25}{143}$	$\frac{24}{143}$	$\frac{21}{143}$	$\frac{16}{143}$	$\frac{9}{143}$	0	$\frac{-11}{143}$				
4	$\frac{162}{1105}$	$\frac{162}{1105}$	$\frac{147}{1105}$	$\frac{122}{1105}$	$\frac{87}{1105}$	$\frac{42}{1105}$	$\frac{-13}{1105}$	$\frac{-78}{1105}$			
8	$\frac{43}{323}$	$\frac{42}{323}$	$\frac{39}{323}$	$\frac{34}{323}$	$\frac{27}{323}$	$\frac{-6}{323}$	$\frac{7}{323}$	$\frac{-6}{323}$	$\frac{-21}{323}$		
8	$\frac{269}{2261}$	$\frac{264}{2261}$	$\frac{249}{2261}$	$\frac{224}{2261}$	$\frac{189}{2261}$	$\frac{144}{2261}$	$\frac{89}{2261}$	$\frac{24}{2261}$	$\frac{-51}{2261}$	$\frac{-136}{2261}$	
10	$\frac{329}{3059}$	$\frac{324}{3059}$	$\frac{309}{3059}$	$\frac{284}{3059}$	$\frac{249}{3059}$	$\frac{204}{3059}$	$\frac{149}{3059}$	$\frac{84}{3059}$	$\frac{9}{3059}$	$\frac{-76}{3059}$	$\frac{-171}{3059}$

Note: $C_1 = C_{-1}$

<u>CoolRate.Y</u>: This program takes inputs of t vs. T and outputs results of dT/dt vs. T. The value of $(dT/dt)_j$ is calculated as $(T_i - T_{i-1})/(t_i - t_{i-1})$ with T_j equal to $(T_i + T_{i-1})/2$. An example of the results is presented in figure 1, from which phase-transformation temperatures can be determined. As shown in figure 1, the first peak, starting at 415 and finishing at 295°C, represents the bainitic transformation, and the second peak, starting at 295 and finishing at 140°C, is the martensitic transformation.

<u>D*l*dTAnal.Y</u>: This program takes input of T vs. l and outputs results of dl/dT vs. T. The value of $(dl/dT)_j$ is calculated as $(l_i - l_{i-1})/(T_i - T_{i-1})$ with T_j equal to $(T_i + Y_{i-1})/2$. An example of the results is presented in figure 2, from which phase-transformation temperatures can be determined. As shown in figure 2, the first peak, starting at 425 and finishing at 295°C, represents the bainitic transformation, and the second peak, starting at 295 and finishing at 140°C, is the martensitic transformation. The figure can also be used to estimate the

thermal expansion coefficients of austenite and ferrite (in the case of figure 2, it is martensite) by dividing dl/dT by the specimen's length. The thermal expansion coefficients, estimated from figure 2 are 25 x 10^{-6} and 11 x 10^{-6}/°C (at 140°C) for austenite and martensite, respectively. The T-vs.-l curve is given in figure 3, which is needed to determine the progression (in volume fraction) of transformation from austenite to its transformation products, such as ferrite, bainite, or martensite, during continuous cooling. The details of determining the progression of transformation are explained in reference 5 of this report. The determination of phase-transformation temperatures is based on the results of dT/dt vs. T, dl/dT vs. T, and the metallographic examinations.

StrStrn.Y: This program requires the input information of D vs. P, specimen's original length, l_o, specimen's original diameter, d_o (the specimen is a cylinder), and the exact position, D_o, at which the machine's actuator touches the specimen (the actuator is retracted away from the specimen before the test). The output of the program is a σ-ϵ curve, as shown in figure 4. Three simplifications are made in the calculation of σ and ϵ. First, we have not considered the dimensional changes due to temperature increases and use the dimensions (length and area) measured at room temperature for calculations. Using the results of thermal linear expansions compiled in reference 6, we estimate the increases in specimen's length from room temperature to 900, 1000, and 1100°C are 1.1, 1.3, and 1.5 percent, respectively. The values of 1.1, 1.3, and 1.5 percent are approximately the values overestimated in true strain if the length corrections were to be made. The increases in area will be 2.2, 2.6, and 3.0 percent, and the overestimation in true stresses will be 3.3, 3.9, and 4.5 percent, accordingly. At present, we have not attempted to correct the dimensional changes due to temperature increases because the available information about the thermal expansion characteristics of steels are not sufficient for accurately making the corrections. The thermal expansion characteristics of steels depend on composition and the initial condition of a steel.

Second, we have not considered the nonuniform strain distribution during compression within a specimen. Because of barreling arising from friction between the specimen and the die, the strains within the specimen are not uniform. The strains are highest at the center of a specimen and lowest near the surface. With the specimen geometry under consideration (a cylinder with a 2-to-1 ratio), taking into account of the non-uniformity of strain distribution has little effect on the calculated σ-ϵ results [7,8].

Third, strains are not calculated from measurements made directly on the specimen. Instead, they are calculated from the actuator's displacement which is measured away from the specimen. The displacement consists of the compliances (displacement divided by load) of the specimen plus the load train. Because the compliance of the specimen is much greater than that of the load train due to the difference in cross-sectional areas of the specimen and the load train, we assume the measured actuator's displacement is due to the compliance of the specimen alone. This assumption is not adequate in areas of small strains because the value of Young's modulus calculated from the σ-ϵ curve is about 50 percent low. Attempts have been made to correct the compliance due to the load train. Unfortunately, no satisfactory results have been obtained.

The values of stress and strain are calculated using the following equations [9]:

$$\epsilon = \ell n(e + 1), \tag{1}$$

$$\sigma = s\,(e + 1), \tag{2}$$

$$e = \Delta l/l_o, \tag{3}$$

$$s = P/A_o, \tag{4}$$

where e, s, A_o, and Δl are the engineering strain, the engineering stress, the specimen's original cross-sectional area, and the specimen's length change during compression, respectively. The values of Δl are computed from the machine's actuator movement.

StrnRate.Y: This program takes inputs of D vs. t, l_o, and the exact position at which the machine's actuator touches the specimen. The output is a $\dot{\epsilon}$-vs.-total ϵ curve, as shown in figure 5.

III. EXAMPLE OF PROGRAM EXECUTION

Input Data Files: Each of the four programs described in the previous section takes input data files in the ASCII format. As previously mentioned, the recorded raw data cannot be read by a PC and have to be processed with digital-processing software [2]. The software is menu-driven, so the details of running the software are not described in this report. Figure 6 shows a partial list of a temperature data file in the ASCII format right after the raw data were processed. The first 13 lines in figure 6 are comments, which are deleted using a full-screen editor. An actual input data file has the exact form as that shown in figure 7.

Running of the Programs: The programs were written in the interactive mode. An example of the prompts for running the program, D*l*dTAnal.Y, is shown in the next paragraph. The prompts for running the other three programs are similar and are not shown in this report. In the following example, ***italicized bold*** letters are the operator's responses to the computer's prompts. There are two input files. One contains temperature data which are stored in C:TEMP.DAT. The other contains specimen's relative length data which are stored in C:DILATION.DAT.

After the program is loaded into the computer, the computer screen prompts OK and the program waits for "WORDS" to perform tasks. Currently, there are 9 options (WORDS) in the program of D*l*dTAnal.Y:

Proceed: This option simply converts the data from voltages to temperature in degree centigrade and to specimen's length in micron. No smoothing is done in this option.

Proceed0: This option calculates dl/dT vs. T with no smoothing on either l or T.

Proceed5: This option calculates dl/dT vs. T with 5-point smoothing on both l and T.

. . .

. . .

Proceed17: This option calculates dl/dT vs. T with 17-point smoothing on both l and T.

At the OK prompt, the operator types in one of the above options. In the following example, we will use Proceed7.

OK ***Proceed7 <Enter>***. The screen will show

. . . Enter the Exact Filename Containing Temperature Data in ASCII . . .
. . . . *C:TEMP.DAT* ***<Enter>***

. . . Enter the Exact Filename Containing Dilation Data in ASCII . . .
. . . . *C:DILATION.DAT* ***<Enter>***

The screen shows a graph of T vs. dl/dT and the program waits for a further command with the prompt of "Hit Any Key to Continue." After the operator presses any key, the screen prompts

Type in a Filename for ASCII Output
That Will Contain Temp-vs.-dldT Data (7-point Smoothed)
. . . . *C:dldT-T7.DAT* ***<Enter>***

This completes the calculation of T vs. dl/dT with 7-point smoothing on both l and T.

<u>Output Data file</u>: The output data file is dldT-T7.DAT, which is in the ASCII format. A partial listing of the file is presented in figure 8.

<u>Graphics</u>: Currently, we use a commercial graphics package listed in reference 10. The package is menu-driven, and the details of running the software are not described in this report. Figures 1 through 5 were plotted with this package.

IV. SUMMARY AND CONCLUDING REMARKS

This report described the data-reduction procedures and computer programs used to reduce and analyze the data obtained with a previously described hot-deformation apparatus. The measured raw data include temperature vs. time, specimen's relative length (dilation) vs. time, machine's actuator movement (stroke) vs. time, and load vs. time. Four computer programs were written for data reduction and analysis to determine the cooling rates, the true stress-true strain curves, the true strain rates, and the phase-transformation temperatures. Local averaging was used to smooth the data of temperature, dilation, stroke, and load.

Currently, four separate programs were written to perform the tasks. The programs use the same averaging techniques. Thus, if desired, the four programs can be consolidated and integrated into one program. This is being pursued at the present in our laboratory.

V. ACKNOWLEDGMENTS

The authors thank A. Massihzadeh for developing portions of the computer programs.

VI. REFERENCES

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[2]* Vu-Point, S-Cubed: A Division of Maxwell Laboratories, Inc., P.O. Box 1620, La Jolla, CA 92038.

[3]* ASYST Software Technologies, Inc., 100 Corporate Woods, Rochester, NY.

[4] C. VanTyne, Colorado School of Mines, Golden, CO, private communication.

[5] M. Atkins, Atlas of Continuous Cooling Transformation Diagrams for Engineering Steels, American Society for Metals, Metals Park, OH, 1980.

[6] Thermophysical Properties of Matter-Metallic Elements and Alloys, the TPRC Data Series, Vol. 12, p. 1166.

[7] J. C. Gelin, J. Oudin, and Y. Ravaland, "Determination of the Flow Stress-Strain Curves for Metals from Axisymmetric Upsetting," J. of Mechanical Working Technology, 5, (1981), pp. 297-308.

[8] D. L. Baragar, "The High Temperature and High Stain-Rate Behavior of a Plain Carbon and an HSLA Steel," J. of Mechanical Working Technology, 14 (1987), pp. 295-307.

[9] G. E. Dieter, Mechanical Metallurgy, 2nd edition, McGraw-Hill Book Company, 1976.

[10]* Grapher, Golden Software, Inc., P. O. Box 281, Golden, CO 80402.

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* These are commercial systems that are mentioned for identification only; no endorsement is intended.

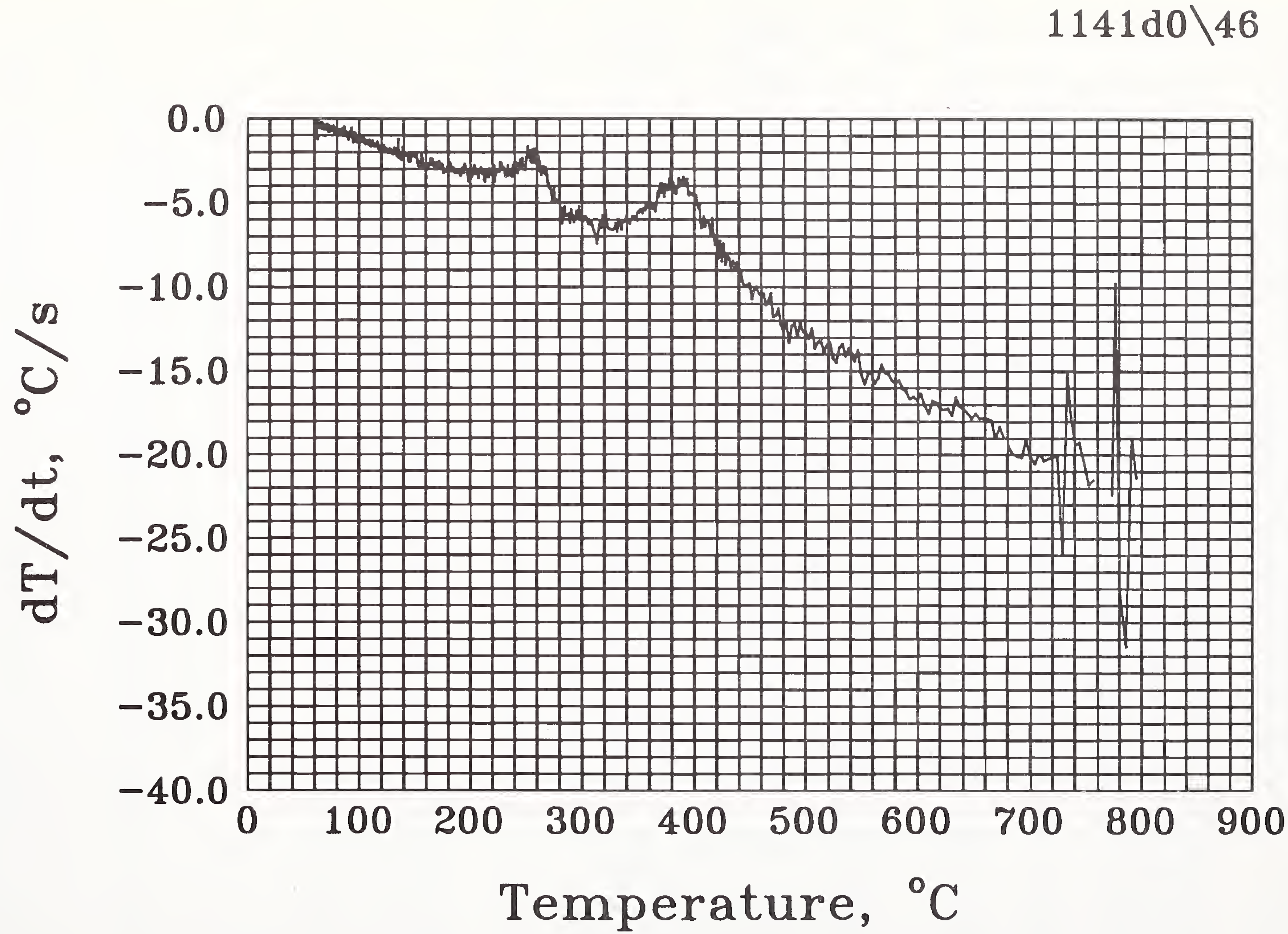

Figure 1. Results of dT/dt vs. T. The graph shows the actual cooling rate during the experiment and gives the indications of phase transformation.

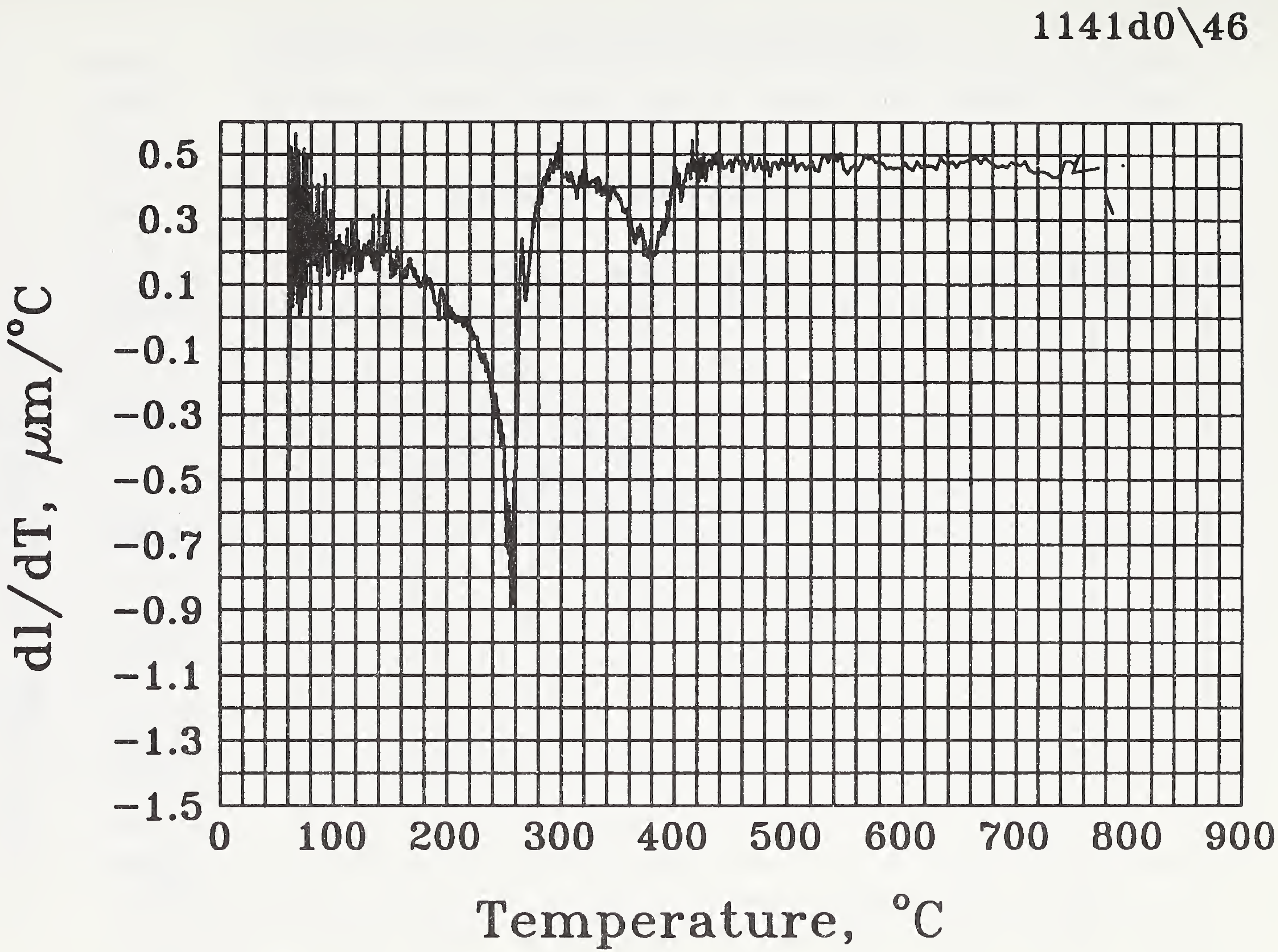

Figure 2. Results of dl/dT vs. T. The graph is used to determine the phase-transformation temperatures and to estimate the thermal expansion coefficients.

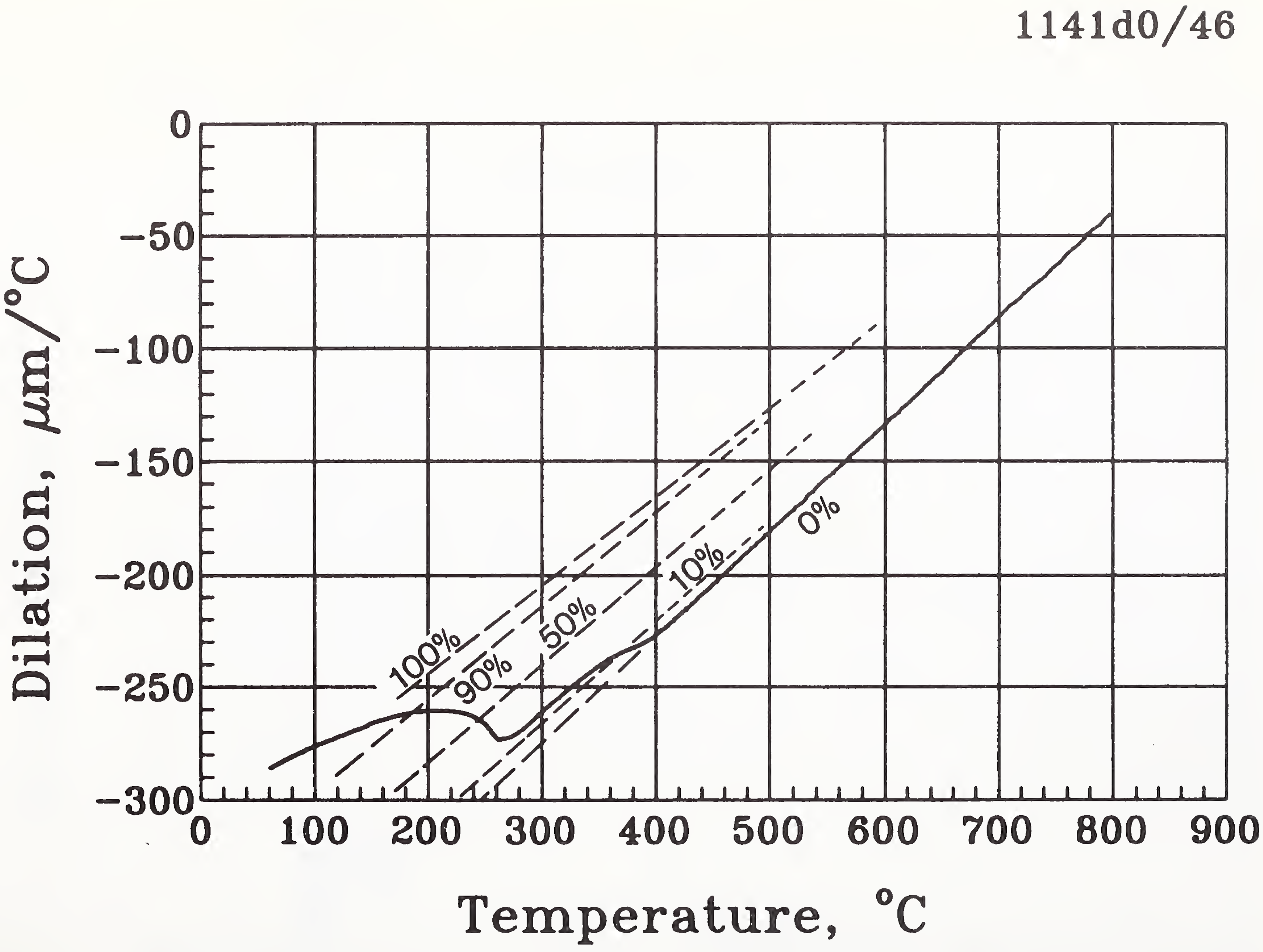

Figure 3. Specimen's length changes due to temperature changes and phase transformations. The percentages shown on the figure are the indication of progression of phase transformation in volume fraction.

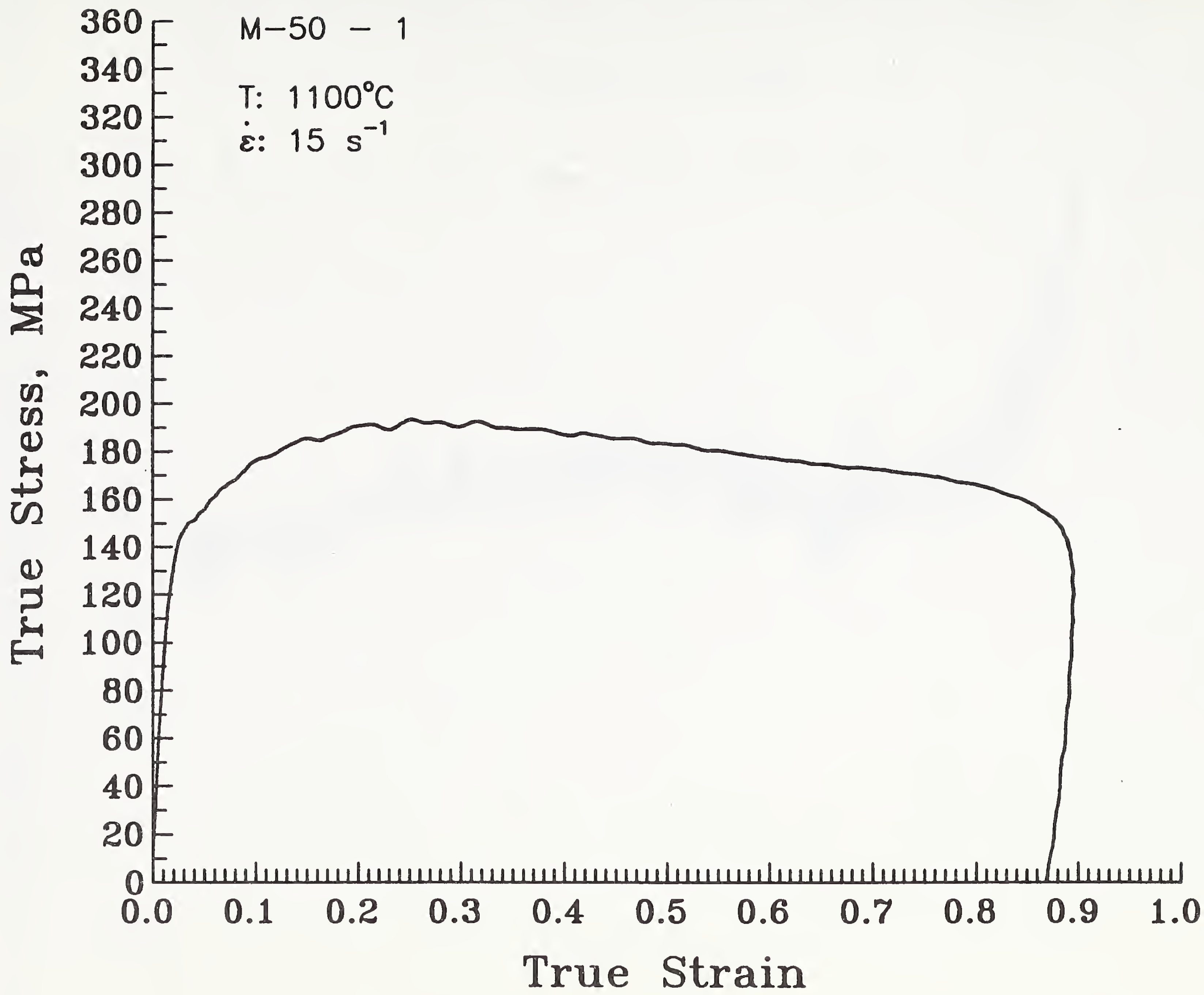

Figure 4. Example of a true stress-true strain curve at high temperature and high strain rate.

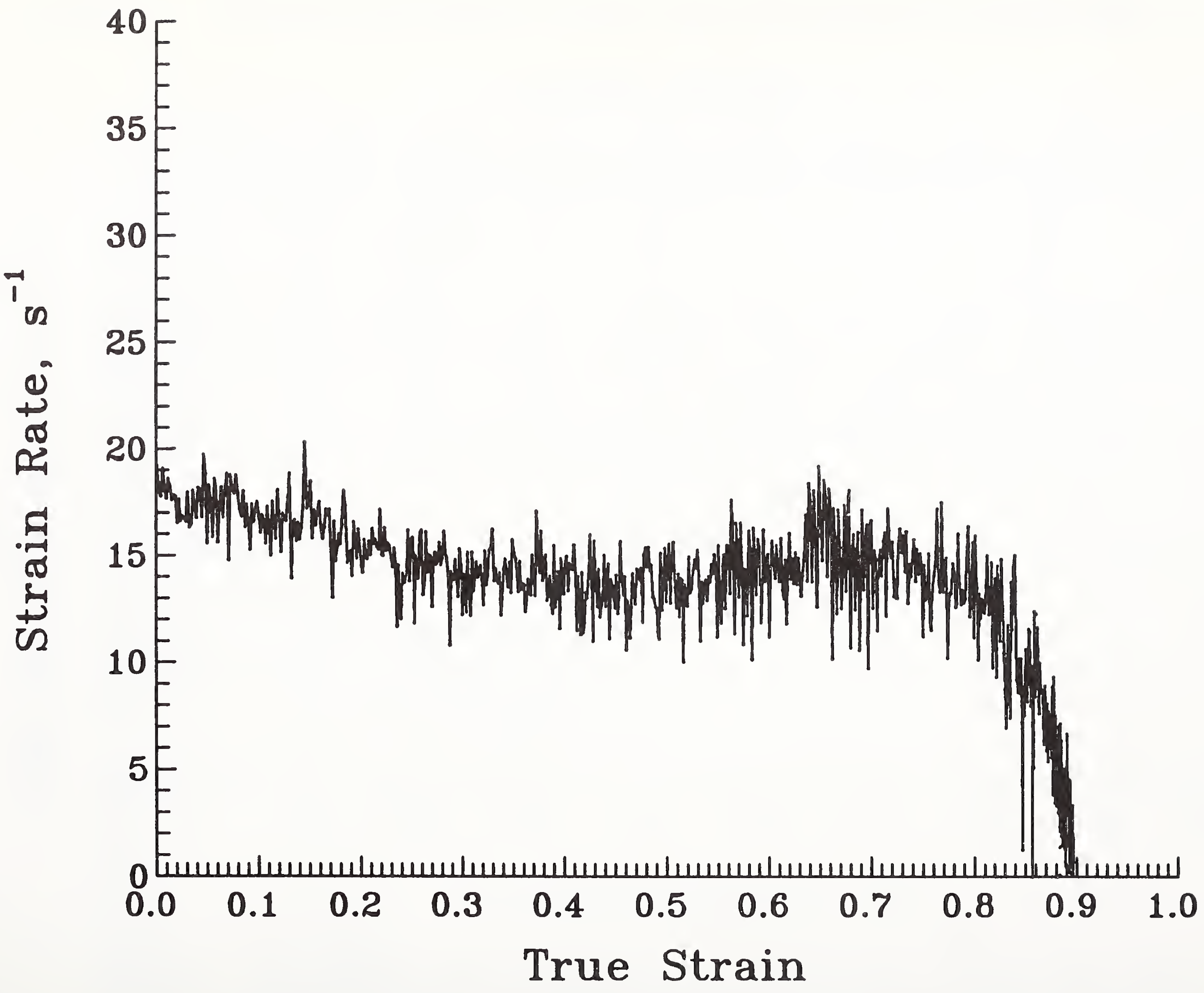

Figure 5. Results of $\dot{\epsilon}$ vs. total ϵ during an experiment.

```
"Data Set # 1  File:TEMP.ad(1Jul90 @ 20:55:08)"
"              Name:Set 1, 1A  ,Q1  "
"             Units:VOLTS"
"            Source:4094 Rec#2"
"           Created:1Jul90 @ 20:53:08"
"     Last-Modified:4094 Rec#2;1Jul90 @ 20:53:08"
"   Sample Interval:500.0ms"
"        Start Time:210.0s"
"          End Time:225.0s"
"  # of Data Points:31"
"  Time is IMPLICIT:See header above."
"            Set #1"
"************"
 1.016687E+00
 1.012625E+00
 1.008125E+00
 1.004000E+00
 9.991875E-01
 9.945000E-01
 9.898750E-01
 9.852500E-01
 9.803750E-01
 9.757500E-01
 9.711875E-01
 9.667500E-01
 9.623125E-01
 9.578750E-01
 9.533750E-01
 9.490625E-01
 9.448750E-01
 9.413750E-01
 9.375625E-01
 9.335625E-01
 9.295000E-01
 9.255000E-01
 9.216250E-01
 9.178125E-01
 9.139375E-01
 9.101250E-01
 9.065000E-01
 9.026250E-01
 8.988750E-01
 8.951250E-01
 8.917500E-01
       .
       .
       .
```

Figure 6. Partial list of a temperature data file in ASCII format after the raw data were processed with the software listed in reference 2. Temperatures are given in voltages.

```
1.016687E+00
1.012625E+00
1.008125E+00
1.004000E+00
9.991875E-01
9.945000E-01
9.898750E-01
9.852500E-01
9.803750E-01
9.757500E-01
9.711875E-01
9.667500E-01
9.623125E-01
9.578750E-01
9.533750E-01
9.490625E-01
9.448750E-01
9.413750E-01
9.375625E-01
9.335625E-01
9.295000E-01
9.255000E-01
9.216250E-01
9.178125E-01
9.139375E-01
9.101250E-01
9.065000E-01
9.026250E-01
8.988750E-01
8.951250E-01
8.917500E-01
    .
    .
    .
```

Figure 7. Example of an input data file.

Temp. (°C)	dl/dT (μm/°C)
1035.99	3.921000E-001
1032.07	3.799000E-001
1028.14	3.920000E-001
1024.15	3.881000E-001
1020.13	3.935000E-001
1016.13	4.015000E-001
1012.22	4.062000E-001
1008.38	4.223000E-001
1004.58	3.942000E-001
1000.77	3.792000E-001
996.949	3.731000E-001
993.21	4.289000E-001
989.679	4.565000E-001
986.359	4.831000E-001
983.096	4.623000E-001
979.749	4.319000E-001
976.332	4.218000E-001
972.909	4.361000E-001
969.532	4.398000E-001
966.188	4.306000E-001
962.875	4.170000E-001
959.603	4.260000E-001
956.388	4.446000E-001
953.127	4.250000E-001
949.833	4.656000E-001
946.589	4.294000E-001
943.505	4.568000E-001
.	.
.	.
.	.

Figure 8. Example of an output data file.

APPENDIX 1 - Computer Program for Cooling-Rate Analysis

```
\***********************************************************************
\                              CoolRate.Y
\***********************************************************************

exp.mem> system.buffer 65280. system.buffer.size      \ To set system buffer size and put the buffer into
                                                         expanded memory

real dim[ 4000 ] array Temp
real dim[ 4000 ] array dTdt
real dim[ 4000 ] array Time

integer scalar g
integer scalar dg
integer scalar k

real scalar c0
real scalar c1
real scalar c2
real scalar c3
real scalar c4
real scalar c5
real scalar c6
real scalar c7
real scalar c8

real scalar dTemp
real scalar dTime

0. temp :=
0. time :=

: go.on \ ******************************************************************
cr ." Hit Any Key" cr
." to Continue" Key Drop ;

: read.temp \ **************************************************************
screen.clear cr cr cr cr cr cr
." ... Enter the Exact Filename Containing Temperature Data in ASCII ..."
cr cr ." . . . . . . . . . .  "  "input defer> basic.open
0 g :=
begin
g 1 + g :=
basic.read drop temp [ g ] :=
?basic.eof
until basic.close g . ;

: read.time \ **************************************************************
cr cr cr cr cr cr
." .... Enter the Time Per Point in Second ..."
cr cr ." . . . . . . . . . . " #input dtime :=
0 time [ 1 ] :=
```

```
g 1 + 1 do
Time [ i ] dtime + Time [ i 1 + ] :=
loop ;

: calculate.temp \ ***********************************************************
temp 10. * temp :=
g 1 + 1 do
temp [ i ] 3. ** 0.104154 *
temp [ i ] 2. ** -3.8403 * +
temp [ i ] 130.286 * +
11.7469 +
temp [ i ] :=
loop ;

: 5point.smoothing \ ***********************************************************
2 k :=
17. 35. / c0 :=
12. 35. / c1 :=
-3. 35. / c2 :=

g 3 - 3 do
k 1 + k :=

temp [ k 2 + ] c2 *
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k ] :=

loop ;

: 7point.smoothing \ ***********************************************************
3 k :=
7. 21. / c0 :=
6. 21. / c1 :=
3. 21. / c2 :=
-2. 21. / c3 :=

g 4 - 4 do
k 1 + k :=

temp [ k 3 + ] c3 *
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k ] :=
```

```
loop ;

: 9point.smoothing \ ***********************************************************
4 k :=
59. 231. / c0 :=
54. 231. / c1 :=
39. 231. / c2 :=
14. 231. / c3 :=
-21. 231. / c4 :=

g 5 - 5 do
k 1 + k :=

temp [ k 4 + ] c4 *
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k ] :=

loop ;

: 11point.smoothing \ *********************************************************
5 k :=
89. 429. / c0 :=
84. 429. / c1 :=
69. 429. / c2 :=
44. 429. / c3 :=
9. 429. / c4 :=
-36. 429. / c5 :=

g 6 - 6 do
k 1 + k :=

temp [ k 5 + ] c5 *
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k ] :=
```

```
loop ;

: 13point.smoothing \ ******************************************************
6 k :=
25. 143. / c0 :=
24. 143. / c1 :=
21. 143. / c2 :=
16. 143. / c3 :=
9. 143. / c4 :=
0. c5 :=
-11. 143. / c6 :=

g 7 - 7 do
k 1 + k :=

temp [ k 6 + ] c6 *
temp [ k 5 + ] c5 * +
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k 6 - ] c6 * +
temp [ k ] :=

loop ;

: 15point.smoothing \ ******************************************************
7 k :=
167. 1105. / c0 :=
162. 1105. / c1 :=
147. 1105. / c2 :=
122. 1105. / c3 :=
87. 1105. / c4 :=
42. 1105. / c5 :=
-13. 1105. / c6 :=
-78. 1105. / c7 :=

g 8 - 8 do
k 1 + k :=

temp [ k 7 + ] c7 *
temp [ k 6 + ] c6 * +
temp [ k 5 + ] c5 * +
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
```

```
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k 6 - ] c6 * +
temp [ k 7 - ] c7 * +
temp [ k ] :=

loop ;

: 17point.smoothing \ ************************************************************
8 k :=
43. 323. / c0 :=
42. 323. / c1 :=
39. 323. / c2 :=
34. 323. / c3 :=
27. 323. / c4 :=
18. 323. / c5 :=
7. 323. / c6 :=
-6. 323. / c7 :=
-21. 323. / c8 :=

g 9 - 9 do
k 1 + k :=

temp [ k 8 + ] c8 *
temp [ k 7 + ] c7 * +
temp [ k 6 + ] c6 * +
temp [ k 5 + ] c5 * +
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k 6 - ] c6 * +
temp [ k 7 - ] c7 * +
temp [ k 8 - ] c8 * +
temp [ k ] :=

loop ;

: Temp.vs.dtdT \ ************************************************************
```

```
1 dg :=
g 1 + 1 do
Temp [ i 1 + ] temp [ i ] - dTemp :=
dTemp ABS 0.00001 > if
dtime ABS 0.00001 > if
dtemp dTime / dtdT [ dg ] :=
Temp [ i 1 + ] Temp [ i ] + 2. / Temp [ dg ] :=
dg 1 + dg :=
then then loop ;

: plot.Temp.vs.dtdT \ ******************************************************
temp sub[ 1 , dg 2. / , 2 ] dtdT sub[ 1 , dg 2. / , 2 ]
graphics.display solid xy.auto.plot ;

: plot.time.vs.temp \ ******************************************************
time sub[ 1 , g 2. / , 2 ]
temp sub[ 1 , g 2. / , 2 ]
graphics.display solid xy.auto.plot ;

: output.to.ASCII.file \ ******************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-time (Nonsmoothed) Data"
cr cr ."                . . . . " "input defer> out>file
console.off
g 1 + 1 do
time [ i ] . ." , " temp [ i ] . cr
loop
out>file.close ;

: output0.to.ASCII.file \ ******************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."              That Will Contain Temp-vs.-dtdT (Nonsmoothed) Data"
cr cr ."                . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: output5.to.ASCII.file \ ******************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-dtdT (5-Point Smoothed) Data"
cr cr ."                . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;
```

```
: output7.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-dtdT (7-Point Smoothed) Data"
cr cr ."                 . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: output9.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-dtdT (9-Point Smoothed) Data"
cr cr ."                 . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: output11.to.ASCII.file \ ***************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dtdT (11-Point Smoothed) Data"
cr cr ."                . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: output13.to.ASCII.file \ ***************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dtdT (13-Point Smoothed) Data"
cr cr ."                . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: output15.to.ASCII.file \ ***************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dtdT (15-Point Smoothed) Data"
cr cr ."                . . . . " "input defer> out>file
console.off
dg 1 + 1 do
```

```
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: output17.to.ASCII.file \ ***************************************************
screen.clear normal.display cr cr cr cr cr cr
."                        Type in a Filename for ASCII Output" cr
."             That Will Contain Temp-vs.-dtdT (17-Point Smoothed) Data"
cr cr ."                 . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dtdT [ i ] . cr
loop
out>file.close ;

: proceed \ ***************************************************************
read.temp calculate.temp
read.time
plot.time.vs.temp go.on output.to.ASCII.file ;

: proceed0 \ **************************************************************
read.temp calculate.temp
read.time
Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output0.to.ASCII.file ;

: proceed5 \ **************************************************************
read.temp calculate.temp
read.time
5point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output5.to.ASCII.file ;

: proceed7 \ **************************************************************
read.temp calculate.temp
read.time
7point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output7.to.ASCII.file ;

: proceed9 \ **************************************************************
read.temp calculate.temp
read.time
9point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output9.to.ASCII.file ;

: proceed11 \ *************************************************************
read.temp calculate.temp
read.time
11point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output11.to.ASCII.file ;

: proceed13 \ *************************************************************
```

```
read.temp calculate.temp
read.time
13point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output13.to.ASCII.file ;

: proceed15 \ **************************************************************
read.temp calculate.temp
read.time
15point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output15.to.ASCII.file ;

: proceed17 \ **************************************************************
read.temp calculate.temp
read.time
17point.smoothing Temp.vs.dtdT plot.Temp.vs.dtdT go.on
output17.to.ASCII.file ;
```

APPENDIX 2 - Computer Program for Temperature-Dilation Analysis

```
\****************************************************************************
\                              d/dTAnal.Y
\****************************************************************************

echo.off
exp.mem> system.buffer 65280. system.buffer.size          \ To set system buffer size and put the buffer into
                                                             expanded memory

real dim[ 4000 ] array temp
real dim[ 4000 ] array dil
real dim[ 4000 ] array dldT

integer scalar g
integer scalar dg
integer scalar k

real scalar c0
real scalar c1
real scalar c2
real scalar c3
real scalar c4
real scalar c5
real scalar c6
real scalar c7
real scalar c8

real scalar dTemp
real scalar dDil

0. temp :=
0. dil :=

: go.on \ *****************************************************************
cr ." Hit Any Key" cr
." to Continue" Key Drop ;

: read.temp \ *************************************************************
screen.clear cr cr cr cr cr cr
." ... Enter the Exact Filename Containing Temperature Data in ASCII ..."
cr cr ." . . . . . . . . . .  "  "input defer> basic.open
0 g :=
begin
g 1 + g :=
basic.read drop temp [ g ] :=
?basic.eof
until basic.close g . ;

: read.dilation \ *********************************************************
cr cr cr cr cr cr
." .... Enter the Exact Filename Containing Dilation Data in ASCII ...."
cr cr ." . . . . . . . . . . " "input defer> basic.open
```

```
0 g :=
begin
g 1 + g :=
basic.read drop dil [ g ] :=
?basic.eof
until basic.close g . ;

: calculate.temp \ ************************************************************
temp 10. * temp :=
g 1 + 1 do

temp [ i ] 3. ** 0.104154 *
temp [ i ] 2. ** -3.8403 * +
temp [ i ] 130.286 * +
11.7469 +
temp [ i ] :=
loop ;

: calculate.dilation \ ************************************************************
g 1 + 1 do

dil [ i ] 92.8878 *
dil [ i ] :=
loop ;

: 5point.smoothing \ ************************************************************
2 k :=
17. 35. / c0 :=
12. 35. / c1 :=
-3. 35. / c2 :=

g 3 - 3 do
k 1 + k :=

temp [ k 2 + ] c2 *
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k ] :=

dil [ k 2 + ] c2 *
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k ] :=
loop ;

: 7point.smoothing \ ************************************************************
3 k :=
```

```
7. 21. / c0 :=
6. 21. / c1 :=
3. 21. / c2 :=
-2. 21. / c3 :=

g 4 - 4 do
k 1 + k :=

temp [ k 3 + ] c3 *
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k ] :=

dil [ k 3 + ] c3 *
dil [ k 2 + ] c2 * +
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k 3 - ] c3 * +
dil [ k ] :=
loop ;

: 9point.smoothing \ ***********************************************************
4 k :=
59. 231. / c0 :=
54. 231. / c1 :=
39. 231. / c2 :=
14. 231. / c3 :=
-21. 231. / c4 :=

g 5 - 5 do
k 1 + k :=

temp [ k 4 + ] c4 *
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k ] :=

dil [ k 4 + ] c4 *
dil [ k 3 + ] c3 * +
```

```
dil [ k 2 + ] c2 * +
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k 3 - ] c3 * +
dil [ k 4 - ] c4 * +
dil [ k ] :=
loop ;

: 11point.smoothing \ ***************************************************************
5 k :=
89. 429. / c0 :=
84. 429. / c1 :=
69. 429. / c2 :=
44. 429. / c3 :=
9. 429. / c4 :=
-36. 429. / c5 :=

g 6 - 6 do
k 1 + k :=

temp [ k 5 + ] c5 *
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k ] :=

dil [ k 5 + ] c5 *
dil [ k 4 + ] c4 * +
dil [ k 3 + ] c3 * +
dil [ k 2 + ] c2 * +
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k 3 - ] c3 * +
dil [ k 4 - ] c4 * +
dil [ k 5 - ] c5 * +
dil [ k ] :=
loop ;

: 13point.smoothing \ ***************************************************************
6 k :=
```

```
25. 143. / c0 :=
24. 143. / c1 :=
21. 143. / c2 :=
16. 143. / c3 :=
9. 143. / c4 :=
0. c5 :=
-11. 143. / c6 :=

g 7 - 7 do
k 1 + k :=

temp [ k 6 + ] c6 *
temp [ k 5 + ] c5 * +
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k 6 - ] c6 * +
temp [ k ] :=

dil [ k 6 + ] c6 *
dil [ k 5 + ] c5 * +
dil [ k 4 + ] c4 * +
dil [ k 3 + ] c3 * +
dil [ k 2 + ] c2 * +
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k 3 - ] c3 * +
dil [ k 4 - ] c4 * +
dil [ k 5 - ] c5 * +
dil [ k 6 - ] c6 * +
dil [ k ] :=
loop ;

: 15point.smoothing \ ***********************************************************
7 k :=
167. 1105. / c0 :=
162. 1105. / c1 :=
147. 1105. / c2 :=
122. 1105. / c3 :=
87. 1105. / c4 :=
42. 1105. / c5 :=
-13. 1105. / c6 :=
```

```
-78. 1105. / c7 :=

g 8 - 8 do
k 1 + k :=

temp [ k 7 + ] c7 *
temp [ k 6 + ] c6 * +
temp [ k 5 + ] c5 * +
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k 6 - ] c6 * +
temp [ k 7 - ] c7 * +
temp [ k ] :=

dil [ k 7 + ] c7 *
dil [ k 6 + ] c6 * +
dil [ k 5 + ] c5 * +
dil [ k 4 + ] c4 * +
dil [ k 3 + ] c3 * +
dil [ k 2 + ] c2 * +
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k 3 - ] c3 * +
dil [ k 4 - ] c4 * +
dil [ k 5 - ] c5 * +
dil [ k 6 - ] c6 * +
dil [ k 7 - ] c7 * +
dil [ k ] :=
loop ;

: 17point.smoothing \ ************************************************************
8 k :=
43. 323. / c0 :=
42. 323. / c1 :=
39. 323. / c2 :=
34. 323. / c3 :=
27. 323. / c4 :=
18. 323. / c5 :=
7. 323. / c6 :=
-6. 323. / c7 :=
-21. 323. / c8 :=
```

```
g 9 - 9 do
k 1 + k :=

temp [ k 8 + ] c8 *
temp [ k 7 + ] c7 * +
temp [ k 6 + ] c6 * +
temp [ k 5 + ] c5 * +
temp [ k 4 + ] c4 * +
temp [ k 3 + ] c3 * +
temp [ k 2 + ] c2 * +
temp [ k 1 + ] c1 * +
temp [ k ] c0 * +
temp [ k 1 - ] c1 * +
temp [ k 2 - ] c2 * +
temp [ k 3 - ] c3 * +
temp [ k 4 - ] c4 * +
temp [ k 5 - ] c5 * +
temp [ k 6 - ] c6 * +
temp [ k 7 - ] c7 * +
temp [ k 8 - ] c8 * +
temp [ k ] :=

dil [ k 8 + ] c8 *
dil [ k 7 + ] c7 * +
dil [ k 6 + ] c6 * +
dil [ k 5 + ] c5 * +
dil [ k 4 + ] c4 * +
dil [ k 3 + ] c3 * +
dil [ k 2 + ] c2 * +
dil [ k 1 + ] c1 * +
dil [ k ] c0 * +
dil [ k 1 - ] c1 * +
dil [ k 2 - ] c2 * +
dil [ k 3 - ] c3 * +
dil [ k 4 - ] c4 * +
dil [ k 5 - ] c5 * +
dil [ k 6 - ] c6 * +
dil [ k 7 - ] c7 * +
dil [ k 8 - ] c8 * +
dil [ k ] :=
loop ;

: Temp.vs.dldT \ ****************************************************************
1 dg :=
g 1 + 1 do
Temp [ i 1 + ] temp [ i ] - dTemp :=
Dil [ i 1 + ] Dil [ i ] - dDil :=
dTemp ABS 0.00001 > if
dDil ABS 0.00001 > if
dDil dTemp / dldT [ dg ] :=
Temp [ i 1 + ] Temp [ i ] + 2. / Temp [ dg ] :=
```

```
dg 1 + dg :=
then then loop ;

: plot.Temp.vs.dldT \ *******************************************************
temp sub[ 1 , dg 2. / , 2 ] dldT sub[ 1 , dg 2. / , 2 ]
graphics.display solid xy.auto.plot ;

: plot.temp.vs.dilation \ ****************************************************
temp sub[ 1 , g 2. / , 2 ]
dil sub[ 1 , g 2. / , 2 ]
graphics.display solid xy.auto.plot ;

: output.to.ASCII.file \ *****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-Dilation (Nonsmoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
g 1 + 1 do
temp [ i ] . ." , " dil [ i ] . cr
loop
out>file.close ;

: output0.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."              That Will Contain Temp-vs.-dldT (Nonsmoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output5.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-dldT (5-Point Smoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output7.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-dldT (7-Point Smoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
```

```
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output9.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."            That Will Contain Temp-vs.-dldT (9-Point Smoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output11.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dldT (11-Point Smoothed) Data"
cr cr ."                 . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output13.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dldT (13-Point Smoothed) Data"
cr cr ."                 . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output15.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dldT (15-Point Smoothed) Data"
cr cr ."                 . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: output17.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
```

```
."                    Type in a Filename for ASCII Output" cr
."           That Will Contain Temp-vs.-dldT (17-Point Smoothed) Data"
cr cr ."              . . . . " "input defer> out>file
console.off
dg 1 + 1 do
temp [ i ] . ." , " dldT [ i ] . cr
loop
out>file.close ;

: proceed \ ****************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
plot.temp.vs.dilation go.on output.to.ASCII.file ;

: proceed0 \ ***************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
Temp.vs.dldT plot.Temp.vs.dldT go.on
output0.to.ASCII.file ;

: proceed5 \ ***************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
5point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output5.to.ASCII.file ;

: proceed7 \ ***************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
7point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output7.to.ASCII.file ;

: proceed9 \ ***************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
9point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output9.to.ASCII.file ;

: proceed11 \ **************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
11point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output11.to.ASCII.file ;

: proceed13 \ **************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
13point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output13.to.ASCII.file ;

: proceed15 \ **************************************************************
```

```
read.temp calculate.temp
read.dilation calculate.dilation
15point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output15.to.ASCII.file ;

: proceed17 \ ***************************************************************
read.temp calculate.temp
read.dilation calculate.dilation
17point.smoothing Temp.vs.dldT plot.Temp.vs.dldT go.on
output17.to.ASCII.file ;
```

APPENDIX 3 - Computer Program for True Stress-True Strain Analysis

```
\*****************************************************************************
\                                        StrStrn.Y
\*****************************************************************************

echo.off
exp.mem> system.buffer 65280. system.buffer.size         \ To set system buffer size and put the buffer into
                                                           expanded memory

real dim[ 1500 ] array Loadd
real dim[ 1500 ] array Stroke
real dim[ 1500 ] array tSTRS
real dim[ 1500 ] array tSTRN
real dim[ 1500 ] array eSTRS
real dim[ 1500 ] array eSTRN

integer scalar g
integer scalar dg
integer scalar kk

real scalar c0
real scalar c1
real scalar c2
real scalar c3
real scalar c4
real scalar c5
real scalar c6
real scalar c7
real scalar c8

    scalar LoadFactr
    scalar StrokeFactr
    scalar Length
    scalar Diameter
    scalar Area
    scalar Stroke0
    scalar MTSComplys

0. Loadd :=
0. Stroke :=
0. tSTRS :=
0. tSTRN :=
0. eSTRN :=
0. eSTRS :=

vuport vu1 0 0.21 vuport.orig 1 0.79 vuport.size 20 0 25 80 window vu2

: go.on \ *******************************************************************
cr ." Hit Any Key" cr
." to Continue" Key Drop ;

: read.load \ ***************************************************************
```

```
screen.clear cr cr cr cr cr cr
."        ... Enter the Exact Filename Containing Load Data in ASCII ..."
cr cr ."        . . . . . . . .  "  "input defer> basic.open
0 g :=
begin
g 1 + g :=
basic.read drop Loadd [ g ] :=
?basic.eof
until basic.close g . ;

: read.load.factor \ **************************************************************
cr cr cr cr cr cr
."          .... Enter the Load Calibration Factor in Newton/Volt ...."
cr cr ."          . . . . . . .   " #input Loadfactr := ;

: read.stroke \ ******************************************************************
screen.clear cr cr cr cr
."        .... Enter the Exact Filename Containing Stroke Data in ASCII ...."
cr cr ."       . . . . . . . . " "input defer> basic.open
0 g :=
begin
g 1 + g :=
basic.read drop Stroke [ g ] :=
?basic.eof
until basic.close g . ;

: read.stroke.factor \ ***********************************************************
cr cr cr cr
."             .... Enter the Stroke Calibration Factor in mm/Volt ...."
cr cr ."           . . . . . . . .   " #input StrokeFactr :=
cr cr cr cr
."        .... Enter the Exact Voltage When Actuator Touches Specimen ...."
cr cr ."      . . . . . . . . . .    " #input Stroke0 :=
;

: calculate.Load.and.Stroke \ ****************************************************
g 1 + 1 do
Loadd [ i ] LoadFactr * Loadd [ i ] :=
19.4701e-6 Loadd [ i ] * MTSComplys :=
Stroke [ i ] Stroke0 -              \ Convert stroke to
StrokeFactr *                       \ displacement regardless whether
MTSComplys -                          \ it is tension or compression
Stroke [ i ] :=
loop ;

: read.specimen.information \ ****************************************************
screen.clear cr cr cr
."              .... Enter the Specimen Length in mm"
cr cr ."              . . . . . .  " #input length :=
cr cr cr cr cr
."             .... Enter the Specimen Diameter in mm"
```

```
cr cr ."                    . . . . . . " #input diameter := ;

: 5point.smoothing \ **********************************************************
2 kk :=
17. 35. / c0 :=
12. 35. / c1 :=
-3. 35. / c2 :=

g 3 - 3 do
kk 1 + kk :=

loadd [ kk 2 + ] c2 *
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk ] :=

stroke [ kk 2 + ] c2 *
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk ] :=
loop ;

: 7point.smoothing \ **********************************************************
3 kk :=
7. 21. / c0 :=
6. 21. / c1 :=
3. 21. / c2 :=
-2. 21. / c3 :=

g 4 - 4 do
kk 1 + kk :=

loadd [ kk 3 + ] c3 *
loadd [ kk 2 + ] c2 * +
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk 3 - ] c3 * +
loadd [ kk ] :=

stroke [ kk 3 + ] c3 *
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
```

```
stroke [ kk 3 - ] c3 * +
stroke [ kk ] :=
loop ;

: 9point.smoothing \ ***********************************************************
4 kk :=
59. 231. / c0 :=
54. 231. / c1 :=
39. 231. / c2 :=
14. 231. / c3 :=
-21. 231. / c4 :=

g 5 - 5 do
kk 1 + kk :=

loadd [ kk 4 + ] c4 *
loadd [ kk 3 + ] c3 * +
loadd [ kk 2 + ] c2 * +
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk 3 - ] c3 * +
loadd [ kk 4 - ] c4 * +
loadd [ kk ] :=

stroke [ kk 4 + ] c4 *
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk ] :=
loop ;

: 11point.smoothing \ *********************************************************
5 kk :=
89. 429. / c0 :=
84. 429. / c1 :=
69. 429. / c2 :=
44. 429. / c3 :=
9. 429. / c4 :=
-36. 429. / c5 :=

g 6 - 6 do
kk 1 + kk :=

loadd [ kk 5 + ] c5 *
```

```
loadd [ kk 4 + ] c4 * +
loadd [ kk 3 + ] c3 * +
loadd [ kk 2 + ] c2 * +
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk 3 - ] c3 * +
loadd [ kk 4 - ] c4 * +
loadd [ kk 5 - ] c5 * +
loadd [ kk ] :=

stroke [ kk 5 + ] c5 *
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk ] :=
loop ;

: 13point.smoothing \ ******************************************************
6 kk :=
25. 143. / c0 :=
24. 143. / c1 :=
21. 143. / c2 :=
16. 143. / c3 :=
9. 143. / c4 :=
0. c5 :=
-11. 143. / c6 :=

g 7 - 7 do
kk 1 + kk :=

loadd [ kk 6 + ] c6 *
loadd [ kk 5 + ] c5 * +
loadd [ kk 4 + ] c4 * +
loadd [ kk 3 + ] c3 * +
loadd [ kk 2 + ] c2 * +
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk 3 - ] c3 * +
loadd [ kk 4 - ] c4 * +
loadd [ kk 5 - ] c5 * +
```

```
loadd [ kk 6 - ] c6 * +
loadd [ kk ] :=

stroke [ kk 6 + ] c6 *
stroke [ kk 5 + ] c5 * +
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk 6 - ] c6 * +
stroke [ kk ] :=
loop ;

: 15point.smoothing \ ********************************************************
7 kk :=
167. 1105. / c0 :=
162. 1105. / c1 :=
147. 1105. / c2 :=
122. 1105. / c3 :=
87. 1105. / c4 :=
42. 1105. / c5 :=
-13. 1105. / c6 :=
-78. 1105. / c7 :=

g 8 - 8 do
kk 1 + kk :=

loadd [ kk 7 + ] c7 *
loadd [ kk 6 + ] c6 * +
loadd [ kk 5 + ] c5 * +
loadd [ kk 4 + ] c4 * +
loadd [ kk 3 + ] c3 * +
loadd [ kk 2 + ] c2 * +
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk 3 - ] c3 * +
loadd [ kk 4 - ] c4 * +
loadd [ kk 5 - ] c5 * +
loadd [ kk 6 - ] c6 * +
loadd [ kk 7 - ] c7 * +
loadd [ kk ] :=

stroke [ kk 7 + ] c7 *
```

```
stroke [ kk 6 + ] c6 * +
stroke [ kk 5 + ] c5 * +
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk 6 - ] c6 * +
stroke [ kk 7 - ] c7 * +
stroke [ kk ] :=
loop ;

: 17point.smoothing \ ***********************************************************
8 kk :=
43. 323. / c0 :=
42. 323. / c1 :=
39. 323. / c2 :=
34. 323. / c3 :=
27. 323. / c4 :=
18. 323. / c5 :=
7. 323. / c6 :=
-6. 323. / c7 :=
-21. 323. / c8 :=

g 9 - 9 do
kk 1 + kk :=

loadd [ kk 8 + ] c8 *
loadd [ kk 7 + ] c7 * +
loadd [ kk 6 + ] c6 * +
loadd [ kk 5 + ] c5 * +
loadd [ kk 4 + ] c4 * +
loadd [ kk 3 + ] c3 * +
loadd [ kk 2 + ] c2 * +
loadd [ kk 1 + ] c1 * +
loadd [ kk ] c0 * +
loadd [ kk 1 - ] c1 * +
loadd [ kk 2 - ] c2 * +
loadd [ kk 3 - ] c3 * +
loadd [ kk 4 - ] c4 * +
loadd [ kk 5 - ] c5 * +
loadd [ kk 6 - ] c6 * +
loadd [ kk 7 - ] c7 * +
loadd [ kk 8 - ] c8 * +
loadd [ kk ] :=
```

```
stroke [ kk 8 + ] c8 *
stroke [ kk 7 + ] c7 * +
stroke [ kk 6 + ] c6 * +
stroke [ kk 5 + ] c5 * +
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk 6 - ] c6 * +
stroke [ kk 7 - ] c7 * +
stroke [ kk 8 - ] c8 * +
stroke [ kk ] :=
loop ;

: calculate.eSTRN.eSTRS \ ****************************************************
Diameter 2. ** pi * 4. / Area :=
g 1 + 1 do
Stroke [ i ] Length / eSTRN [ i ] :=
Loadd [ i ] Area / eSTRS [ i ] :=
loop ;

: calculate.tSTRN.tSTRS \ ****************************************************
g 1 + 1 do
eSTRN [ i ] 1. + Ln -1. * tSTRN [ i ] :=
eSTRN [ i ] 1. + eSTRS [ i ] * -1. * tSTRS [ i ] :=
loop ;

: plot.eSTRN.eSTRS \ *********************************************************
g 1 + 1 do
eSTRN [ i ] -1 * 100 * eSTRN [ i ] :=
eSTRS [ i ] -1 * eSTRS [ i ] :=
loop
eSTRN eSTRS xy.auto.plot ;

: plot.tSTRN.tSTRS \ *********************************************************
screen.clear tSTRN tSTRS xy.auto.plot ;

: output0.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                Type in a Filename for ASCII Output" cr
."      That Will Contain True Stress-vs.-True Strain (Nonsmoothed) Data"
cr cr ."               . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
```

```
loop
out>file.close ;

: output5.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."    That Will Contain True Stress-vs.-True Strain (5-Point Smoothed) Data"
cr cr ."              . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: output7.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."    That Will Contain True Stress-vs.-True Strain (7-Point Smoothed) Data"
cr cr ."              . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: output9.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."    That Will Contain True Stress-vs.-True Strain (9-Point Smoothed) Data"
cr cr ."              . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: output11.to.ASCII.file \ ***************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."   That Will Contain True Stress-vs.-True Strain (11-Point Smoothed) Data"
cr cr ."             . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: output13.to.ASCII.file \ ***************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."   That Will Contain True Stress-vs.-True Strain (13-Point Smoothed) Data"
```

```
cr cr ."                    . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: output15.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                   Type in a Filename for ASCII Output" cr
."    That Will Contain True Stress-vs.-True Strain (15-Point Smoothed) Data"
cr cr ."                    . . . . " "input defer> out>file
console.off
dg 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: output17.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                   Type in a Filename for ASCII Output" cr
."    That Will Contain True Stress-vs.-True Strain (17-Point Smoothed) Data"
cr cr ."                    . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRS [ i ] . cr
loop
out>file.close ;

: proceed0 \ *****************************************************************
read.Load read.load.factor
read.Stroke read.Stroke.Factor calculate.load.and.stroke
read.specimen.information
calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output0.to.ASCII.file ;

: proceed5 \ *****************************************************************
read.Load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
5point.smoothing calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output5.to.ASCII.file ;

: proceed7 \ *****************************************************************
read.load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
7point.smoothing calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
```

```
output7.to.ASCII.file ;

: proceed9 \ **************************************************************
read.load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
9point.smoothing calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output9.to.ASCII.file ;

: proceed11 \ **************************************************************
read.load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
11point.smoothing calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output11.to.ASCII.file ;

: proceed13 \ **************************************************************
read.load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
13point.smoothing calculate.eSTRn.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output13.to.ASCII.file ;

: proceed15 \ **************************************************************
read.load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
15point.smoothing calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output15.to.ASCII.file ;

: proceed17 \ **************************************************************
read.load read.load.factor
read.stroke read.stroke.factor calculate.load.and.stroke
read.specimen.information
17point.smoothing calculate.eSTRN.eSTRS calculate.tSTRN.tSTRS
plot.eSTRN.eSTRS go.on plot.tSTRN.tSTRS go.on
output17.to.ASCII.file ;
```

APPENDIX 4 - Computer Program for Strain-Rate Analysis

```
\*************************************************************************
\                                   StrnRate.Y
\*************************************************************************

echo.off
exp.mem> system.buffer 65280. system.buffer.size        \ To set system buffer size and put the buffer into
                                                          expanded memory

real dim[ 1500 ] array Stroke
real dim[ 1500 ] array tSTRN
real dim[ 1500 ] array eSTRN
real dim[ 1500 ] array eSTRNdt
real dim[ 1500 ] array tSTRNdt

integer scalar g
integer scalar dg
integer scalar kk

real scalar c0
real scalar c1
real scalar c2
real scalar c3
real scalar c4
real scalar c5
real scalar c6
real scalar c7
real scalar c8

   real scalar StrokeFactr
   real scalar Length
   real scalar Stroke0
   real scalar dtime

0. Stroke :=
0. tSTRN :=
0. eSTRN :=
0. eSTRNdt :=
0. tSTRNdt :=
0. dtime :=
vuport vu1 0 0.21 vuport.orig 1 0.79 vuport.size 20 0 25 80 window vu2

: go.on \ *****************************************************************
cr ." Hit Any Key" cr
." to Continue" Key Drop ;

: read.time \ **************************************************************
cr cr cr cr cr cr
."      ... Enter the Time Per Point in Second ..."
cr cr ."       . . . . . . . .  " #input dtime :=
;
```

```
: read.stroke \ ****************************************************************
screen.clear cr cr cr cr
."       .... Enter the Exact Filename Containing Stroke Data in ASCII ...."
cr cr ."       . . . . . . . . " "input defer> basic.open
0 g :=
begin
g 1 + g :=
basic.read drop Stroke [ g ] :=
?basic.eof
until basic.close g . ;

: read.stroke.factor \ *********************************************************
cr cr cr cr
."            .... Enter the Stroke Calibration Factor in mm/Volt ...."
cr cr ."            . . . . . . . .   " #input StrokeFactr :=
cr cr cr cr
."        .... Enter the Exact Voltage When Actuator Touches Specimen ...."
cr cr ."      . . . . . . . . . .    " #input Stroke0 :=
;

: calculate.Stroke \ ***********************************************************
g 1 + 1 do
Stroke [ i ] Stroke0 -                    \ Convert stroke to
StrokeFactr *                             \ displacement regardless whether
Stroke [ i ] :=                           \ it is tension or compression
loop ;

: read.specimen.information \ **************************************************
screen.clear cr cr cr
."                .... Enter the Specimen Length in mm"
cr cr ."               . . . . . .  " #input length := ;

: 5point.smoothing \ ***********************************************************
2 kk :=
17. 35. / c0 :=
12. 35. / c1 :=
-3. 35. / c2 :=

g 3 - 3 do
kk 1 + kk :=

stroke [ kk 2 + ] c2 *
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk ] :=
loop ;

: 7point.smoothing \ ***********************************************************
3 kk :=
```

```
7. 21. / c0 :=
6. 21. / c1 :=
3. 21. / c2 :=
-2. 21. / c3 :=

g 4 - 4 do
kk 1 + kk :=

stroke [ kk 3 + ] c3 *
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk ] :=
loop ;

: 9point.smoothing \ **********************************************************
4 kk :=
59. 231. / c0 :=
54. 231. / c1 :=
39. 231. / c2 :=
14. 231. / c3 :=
-21. 231. / c4 :=

g 5 - 5 do
kk 1 + kk :=

stroke [ kk 4 + ] c4 *
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk ] :=
loop ;

: 11point.smoothing \ ********************************************************
5 kk :=
89. 429. / c0 :=
84. 429. / c1 :=
69. 429. / c2 :=
44. 429. / c3 :=
9. 429. / c4 :=
-36. 429. / c5 :=

g 6 - 6 do
```

```
kk 1 + kk :=


stroke [ kk 5 + ] c5 *
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk ] :=
loop ;

: 13point.smoothing \ ************************************************************
6 kk :=
25. 143. / c0 :=
24. 143. / c1 :=
21. 143. / c2 :=
16. 143. / c3 :=
9. 143. / c4 :=
0. c5 :=
-11. 143. / c6 :=

g 7 - 7 do
kk 1 + kk :=

stroke [ kk 6 + ] c6 *
stroke [ kk 5 + ] c5 * +
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk 6 - ] c6 * +
stroke [ kk ] :=
loop ;

: 15point.smoothing \ ************************************************************
7 kk :=
167. 1105. / c0 :=
162. 1105. / c1 :=
147. 1105. / c2 :=
```

```
122. 1105. / c3 :=
87. 1105. / c4 :=
42. 1105. / c5 :=
-13. 1105. / c6 :=
-78. 1105. / c7 :=

g 8 - 8 do
kk 1 + kk :=

stroke [ kk 7 + ] c7 *
stroke [ kk 6 + ] c6 * +
stroke [ kk 5 + ] c5 * +
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk 6 - ] c6 * +
stroke [ kk 7 - ] c7 * +
stroke [ kk ] :=
loop ;

: 17point.smoothing \ **************************************************************
8 kk :=
43. 323. / c0 :=
42. 323. / c1 :=
39. 323. / c2 :=
34. 323. / c3 :=
27. 323. / c4 :=
18. 323. / c5 :=
7. 323. / c6 :=
-6. 323. / c7 :=
-21. 323. / c8 :=

g 9 - 9 do
kk 1 + kk :=

stroke [ kk 8 + ] c8 *
stroke [ kk 7 + ] c7 * +
stroke [ kk 6 + ] c6 * +
stroke [ kk 5 + ] c5 * +
stroke [ kk 4 + ] c4 * +
stroke [ kk 3 + ] c3 * +
stroke [ kk 2 + ] c2 * +
stroke [ kk 1 + ] c1 * +
stroke [ kk ] c0 * +
```

```
stroke [ kk 1 - ] c1 * +
stroke [ kk 2 - ] c2 * +
stroke [ kk 3 - ] c3 * +
stroke [ kk 4 - ] c4 * +
stroke [ kk 5 - ] c5 * +
stroke [ kk 6 - ] c6 * +
stroke [ kk 7 - ] c7 * +
stroke [ kk 8 - ] c8 * +
stroke [ kk ] :=
loop ;

: calculate.eSTRN \ ***********************************************************
g 1 + 1 do
Stroke [ i ] Length / eSTRN [ i ] :=
loop ;

: calculate.tSTRN \ ***********************************************************
g 1 + 1 do
eSTRN [ i ] 1. + Ln -1. * tSTRN [ i ] :=
loop ;

: calculate.eSTRNdt.tSTRNdt \ ************************************************
g 1 + 1 do
eSTRN [ i 1 + ] eSTRN [ i ] -
dtime / eSTRNdt [ i ] :=
tSTRN [ i 1 + ] tSTRN [ i ] -
dtime / tSTRNdt [ i ] :=
loop ;

: plot.eSTRN.eSTRNdt \ *******************************************************
g 1 + 1 do
eSTRN [ i ] -1 * 100 * eSTRN [ i ] :=
eSTRNdt [ i ] -1 * eSTRNdt [ i ] :=
loop
eSTRN eSTRNdt xy.auto.plot ;

: plot.tSTRN.tSTRNdt \ *******************************************************
screen.clear tSTRN tSTRNdt xy.auto.plot ;

: output0.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."        That Will Contain True Straindt -vs.-True Strain (Nonsmoothed) Data"
cr cr ."                    . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: output5.to.ASCII.file \ ****************************************************
```

```
screen.clear normal.display cr cr cr cr cr cr
."                     Type in a Filename for ASCII Output" cr
."    That Will Contain True Straindt-vs.-True Strain (5-Point Smoothed) Data"
cr cr ."                   . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: output7.to.ASCII.file \ *****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                     Type in a Filename for ASCII Output" cr
."    That Will Contain True Straindt-vs.-True Strain (7-Point Smoothed) Data"
cr cr ."                   . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: output9.to.ASCII.file \ *****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                     Type in a Filename for ASCII Output" cr
."    That Will Contain True Straindt-vs.-True Strain (9-Point Smoothed) Data"
cr cr ."                   . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: output11.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                     Type in a Filename for ASCII Output" cr
."   That Will Contain True Straindt-vs.-True Strain (11-Point Smoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: output13.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                     Type in a Filename for ASCII Output" cr
."   That Will Contain True Straindt-vs.-True Strain (13-Point Smoothed) Data"
cr cr ."                  . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
```

```
loop
out>file.close ;
: output15.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."    That Will Contain True Straindt-vs.-True Strain (15-Point Smoothed) Data"
cr cr ."               . . . . " "input defer> out>file
console.off
dg 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: output17.to.ASCII.file \ ****************************************************
screen.clear normal.display cr cr cr cr cr cr
."                    Type in a Filename for ASCII Output" cr
."    That Will Contain True Straindt-vs.-True Strain (17-Point Smoothed) Data"
cr cr ."               . . . . " "input defer> out>file
console.off
g 1 + 1 do
tSTRN [ i ] . ." , " tSTRNdt [ i ] . cr
loop
out>file.close ;

: proceed0 \ ******************************************************************
read.time
read.Stroke read.Stroke.Factor calculate.stroke
read.specimen.information
calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output0.to.ASCII.file ;

: proceed5 \ ******************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
5point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output5.to.ASCII.file ;

: proceed7 \ ******************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
7point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
```

```
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output7.to.ASCII.file ;

: proceed9 \ ***************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
9point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output9.to.ASCII.file ;

: proceed11 \ ***************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
11point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output11.to.ASCII.file ;

: proceed13 \ ***************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
13point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output13.to.ASCII.file ;

: proceed15 \ ***************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
15point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on
output15.to.ASCII.file ;

: proceed17 \ ***************************************************************
read.time
read.stroke read.stroke.factor calculate.stroke
read.specimen.information
17point.smoothing calculate.eSTRN
calculate.tSTRN
calculate.eSTRNdt.tSTRNdt
plot.eSTRN.eSTRNdt go.on plot.tSTRN.tSTRNdt go.on output17.to.ASCII.file ;
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This report described the data-reduction procedures and computer programs used to reduced and analyze the data obtained with a hot-deformation apparatus. The measured raw data with the apparatus include temperature vs. time, specimen's relative length (dilation) vs. time, actuator movement (stroke) vs. time, and load vs. time. Four computer programs were written for data reduction and analysis to determine the cooling rates, the true stress-true strain curves, the true strain rates, and the phase-transformation temperatures. Local averaging techniques were used to smooth the data of temperature, dilation, stroke, and load. Source codes for the computer programs are included. Example results of the analyses are presented and an example of the program execution is given.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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